WVT-TR-76027

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FRACTURE TOUGHNESS TESTING USING THE
C-SHAPED SPECIMEN

July 1976

# BENET WEAPONS LABORATORY
## WATERVLIET ARSENAL
## WATERVLIET, N.Y.       12189

US ARMY
ARMAMENT
COMMAND

# TECHNICAL REPORT

AMCMS No.   611102.11. H4200

Pron No.  AW-6-R0002-01-AW-M7

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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br><br>WVT-TR-76027 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE *(and Subtitle)*<br><br>Fracture Toughness Testing Using the C-Shaped Specimen | | 5. TYPE OF REPORT & PERIOD COVERED |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br><br>J. H. Underwood<br>D. P. Kendall | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br><br>Benet Weapons Laboratory<br>Watervliet Arsenal, Watervliet, N.Y. 12189<br>SARWV-RT-TP | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>AMCMS No. 611102.11.H4200<br><br>Pron No. AW-6-R0002-01-AW-M7 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br><br>U.S. Army Armament Command<br>Rock Island, Illinois 61201 | | 12. REPORT DATE<br>July 1976 |
| | | 13. NUMBER OF PAGES<br>29 |
| 14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)* | | 15. SECURITY CLASS. *(of this report)*<br><br>UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

Presented at ASTM Symposium on Developments in Fracture Mechanics Test Methods, St. Louis, MO, May 1976.

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

| | |
|---|---|
| Boundary Value Collocation | Thick-Wall Cylinder |
| Fracture (Mechanics) | Toughness |
| Standardized Tests | |

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Fracture toughness testing of material with cylindrical geometry is discussed, and the inherent advantages of the C-shaped specimen in this situation are given. A K calibration equation for the C-shaped specimen is presented which is based on boundary value collocation results. The C-shaped specimen K calibration is compared with those for the standard compact specimen and the single-edge-notched bar specimen.

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Guidelines for measuring plane strain fracture toughness ($K_{Ic}$) using the C-shaped specimen are described, including (a) a $K_I$ calibration which applies over a wide range of diameter ratios and to two load point locations in segments of hollow cylinders, as well as over a range of crack lengths, (b) compliance and crack-mouth-displacement analyses and their use to obtain the critical value of $K_I$ in a fracture toughness test, and (c) suggested specimen geometries to be used in performing $K_{Ic}$ tests with C-shaped specimens.

The use of C-shaped specimens for performing J-integral fracture toughness tests and fatigue crack growth tests is described, and some preliminary testing guidelines are offered. Included are suggested methods of load-point-displacement measurement for J-integral tests and suggestions for the geometry and K calibration which could be used in fatigue tests.

WVT-TR-76027

# FRACTURE TOUGHNESS TESTING USING THE C-SHAPED SPECIMEN
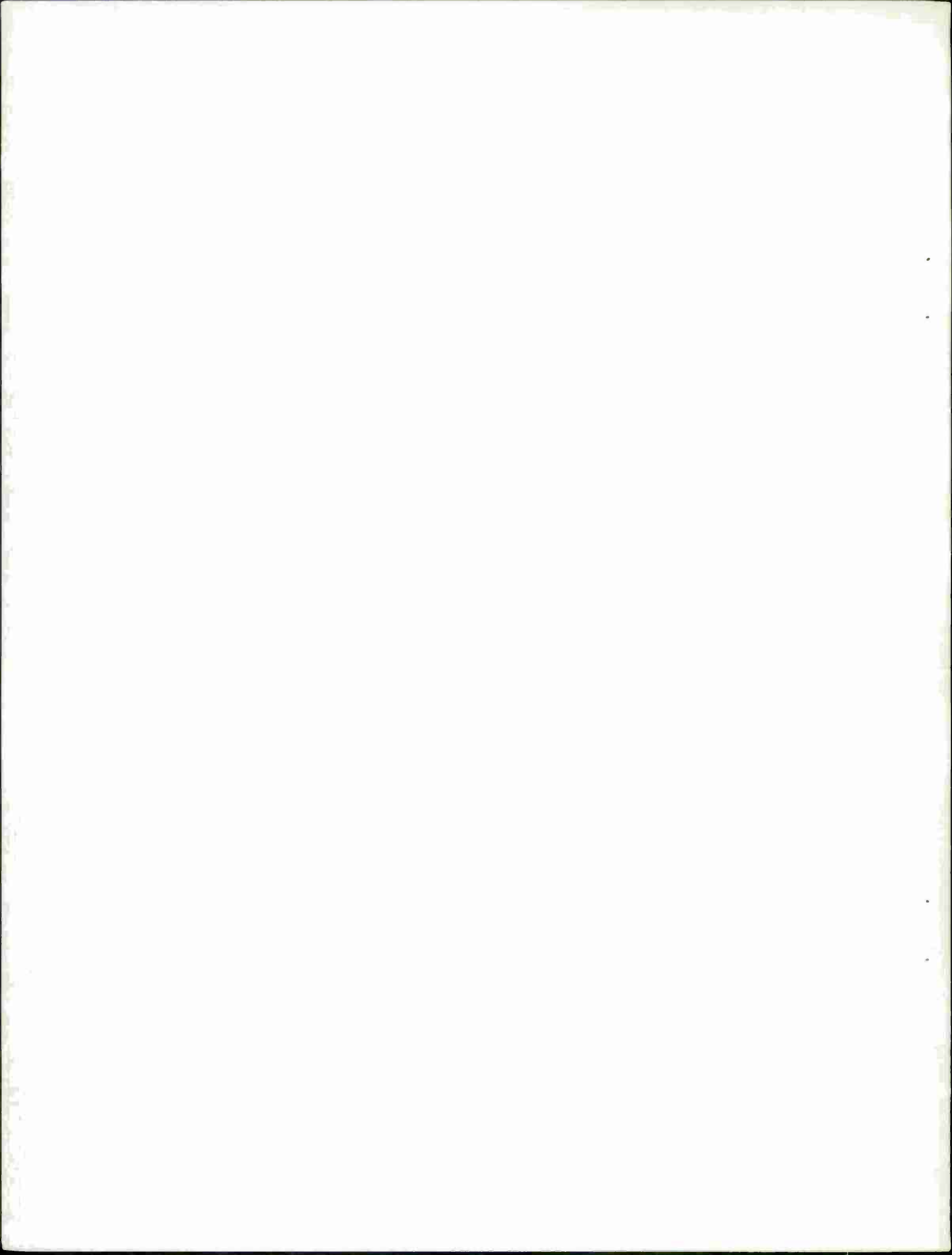
J. H. Underwood
D. P. Kendall

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INTRODUCTION AND OBJECTIVE

The serious consequences of a fracture of a thick-walled cylinder containing a pressurized fluid are obvious. So, all reasonable precautions must be taken to prevent such a fracture. Any rational approach to such prevention requires the knowledge of the plane strain fracture toughness, $K_{Ic}$ of the cylinder material. However, obtaining such knowledge can be more difficult than obtaining $K_{Ic}$ from rectangular shaped bar and plate material.

Except for fractures in the region of end closures, which are not of concern in this paper (although they should be of concern to the designer), most cylinder fractures result from propagation of a crack in a plane normal to the tangential direction. So, any fracture toughness test specimen must be oriented in this direction. As can be seen in Figure 1, this limits the size of the standard ASTM-E399[1] compact specimen that can be made from a given cylinder. This, in turn, limits the range of materials for which valid $K_{Ic}$ results can be obtained, due to the minimum size requirement of E-399.

In order to partially overcome this limitation and also to reduce the expense of machining rectangular shaped specimens from a cylindrical geometry, the authors have developed a new specimen configuration known as the "C-shaped" specimen. This is shown in Figure 1. It consists simply of a portion of a disc cut from the cylinder, provided with holes for pin loading in tension and with a notch and fatigue pre-crack from the bore

[1]1975 Annual Book of ASTM Standards, Part 10, American Society for Testing and Materials, 1975, pp. 561-580.
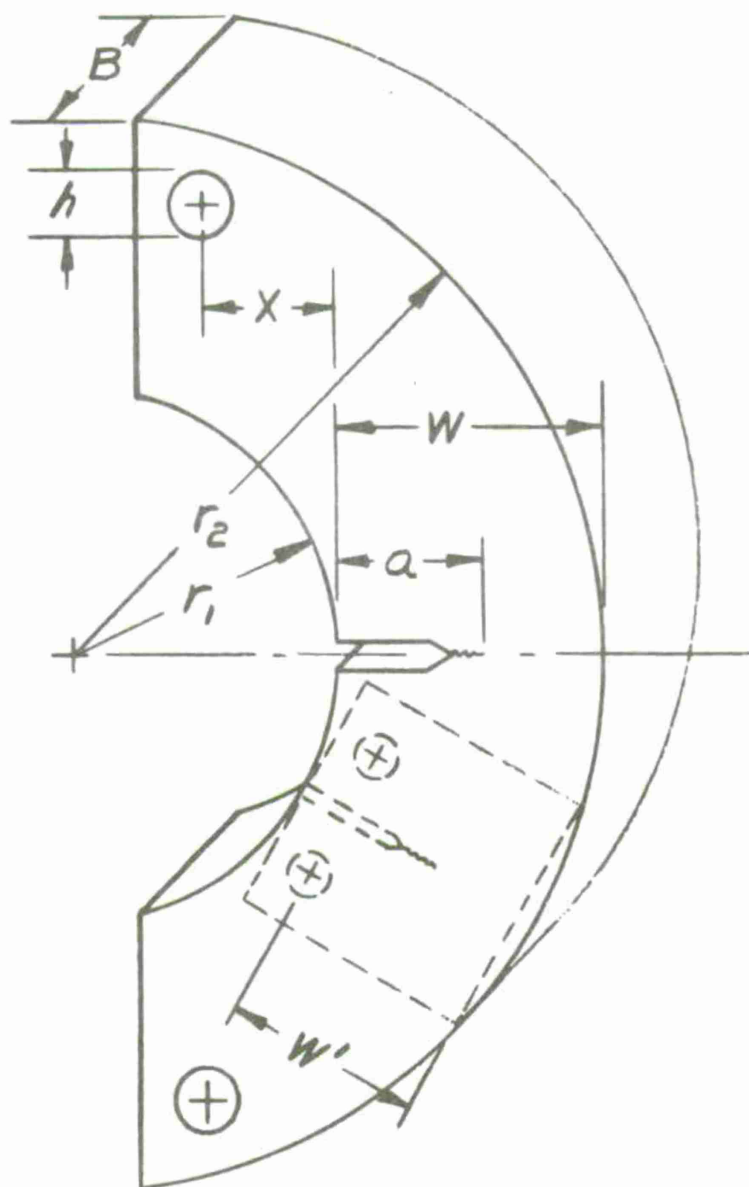
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Figure 1.  C-shaped specimen geometry and symbols.

surface. The inside and outside radii ($r_1$ and $r_2$) are those of the original cylinder. This permits the most efficient use possible of the available material toward achieving plane strain conditions in measuring $K_{Ic}$. For a cylinder having a ratio of outside to inside diameter of 2.0, the effective size of a C-shaped specimen is 32% greater than that of the largest attainable compact specimen.

In designing the C-shaped specimen one is faced with the rather arbitrary decision as to the location of the loading holes and, thus, the portion of the disc which is to be used for the specimen. The hole location is specified by the normal distance between the plane containing the centerlines of the loading holes and the parallel plane tangent to the bore surface. This distance is defined as "X", as shown in Figure 1. Through the activities of ASTM Task Group E24.01.12, it has been determined that nearly all requirements for the use of this specimen can be satisfied by two different relative values of X. These are W/2 and 0. For X = 0, the plane of the loading holes is tangent to the bore surface. The relative advantages of these two designs will be discussed later.

In order to use any fracture toughness specimen, the relationship for the stress intensity factor in terms of the specimen geometry and crack length is required. This relationship, known as the "K calibration" for the specimen, has been determined independently by several individuals using numerical and experimental techniques. These results will be discussed and compared with a general calibration equation proposed by the authors.

A proposed standard $K_{Ic}$ test method using the C-shaped specimen will be presented, and the utilization of this specimen for other tests such as fatigue crack growth measurement and $J_{Ic}$ measurement will be discussed.

K-CALIBRATION RESULTS FOR C-SHAPED SPECIMENS

### K From Collocation

One of the most accurate and most widely used analytical methods for
determining stress intensity factor calibrations for cracked geometries
is the boundary value collocation method. Following the initial development
of the C-shaped specimen[2] the K calibration for several C-shaped geometries
has been determined using the collocation method.[3][4][5] Recently,
Gross and Srawley[6] obtained collocation results which apply over a wide
range of C-shaped geometries, including those of interest for fracture
toughness testing in cylindrical geometries. Based on the collocation
results from references 5 and 6 and on additional collocation results in
relation to ASTM Task Group E24.01.12, a closed form expression has been
obtained which represents a wide range of the C-shaped K results which
have been obtained to date by collocation. This expression is as follows:

$$KBW^{1/2}/P = f(a/W)[1+1.54 \ X/W + 0.50 \ a/W][1+0.22(1-a/W^{1/2}[1-r_1/r_2)]$$

$$f(a/W)=18.23 \ a/W^{1/2}-106.2 \ a/W^{3/2}+379.7 \ a/W^{5/2}-582.0 \ a/W^{7/2}+369.1 \ a/W^{9/2}$$

$$0.3 < a/W < 0.7 \qquad 0 < X/W < 0.7 \qquad 1.0 < r_2/r_1 < \infty \qquad \text{Eq} \quad 1$$

Within the ranges of the three variables indicated, we believe Eq 1
represents the true K-calibration for C-shaped specimens within 2%.

[2]Kendall, D. P. and Hussain, M. A., Experimental Mechanics, Vol 12, Apr 1972,
pp. 184-189.
[3]Hussain, M. A., Lorensen, W. E., Kendall, D. P., and Pu, S. L., "A Modified
Collocation Method for C-Shaped Specimens", Benet Weapons Laboratory
Technical Report, R-WV-T-X-6-73, Watervliet, NY, Feb 1973.
[4]Underwood, J. H., Scanlon, R. D., and Kendall, D. P., "K Calibration for
C-Shaped Specimens of Various Geometries", Fracture Analysis, ASTM STP 560,
American Society for Testing and Materials, 1974, pp. 81-91.
[5]Underwood, J. H. and Kendall, D. P., "K Results and Comparisons for a
Proposed Standard C-Specimen", Benet Weapons Laboratory Technical Report
WVT-TR-74041, Watervliet, NY, Sep 1974.
[6]Gross, B. and Srawley, J. E., "Analysis of Radially Cracked Ring Segments
Subject to Forces and Couples", NASA Tech Memo NASA TM X-71842, Lewis
Research Center, Cleveland, Ohio, 1976.

In Eq 1 $KBW^{1/2}/P$ is a commonly used, dimensionless parameter usable with any set of units. K is the opening mode stress intensity factor, P is the load applied to the specimen, and the other symbols are the specimen dimensions described graphically in Fig 1. Equation 1 is in the same general form often used for K calibrations, such as those of the standard bend and compact specimens of ASTM-E-399.[1] But the equation is more complex due to the fact that K is given as a function of three variables rather than one as is usual. In addition to the usual dependence on crack length (the variable a/W), K for C-shaped specimens depends on the position of the loading hole ($X/W$) and on the radius ratio of the cylinder ($r_2/r_1$). So, although the K expression is more complex, it can be used for specimens from virtually any cylinder.

A plot of K from Eq 1 along with the collocation results from two independent sources[5][6] is shown in Fig 2, for one specific geometry of C-shaped specimen. This plot shows graphically the good agreement between Eq 1 and the collocation results upon which it was based. But, of course, the plot is for only one combination of loading hole location and radius ratio. Each other combination would have a similar plot.

### K From Compliance

A direct experimental method for determining a K calibration is from elastic compliance measurements from the geometry of interest. The development work on the C-shaped specimen included a compliance K calibration,[2]

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[1]1975 Annual Book of ASTM Standards, Part 10, American Society for Testing and Materials, 1975, pp. 561-580.

[2]Kendall, D. P. and Hussain, M. A., Experimental Mechanics, Vol 12, Apr 1972, pp. 184-189.

[5]Underwood, J. H., and Kendall, D. P., "K Results and Comparisons for a Proposed Standard C-Specimen", Benet Weapons Laboratory Technical Report WVT-TR-74041, Watervliet, NY, Sep 1974.

[6]Gross, B., and Srawley, J. E., "Analysis of Radially Cracked Ring Segments Subject to Forces and Couples", NASA Tech Memo NASA TM X-71842, Lewis Research Center, Cleveland, Ohio, 1976.
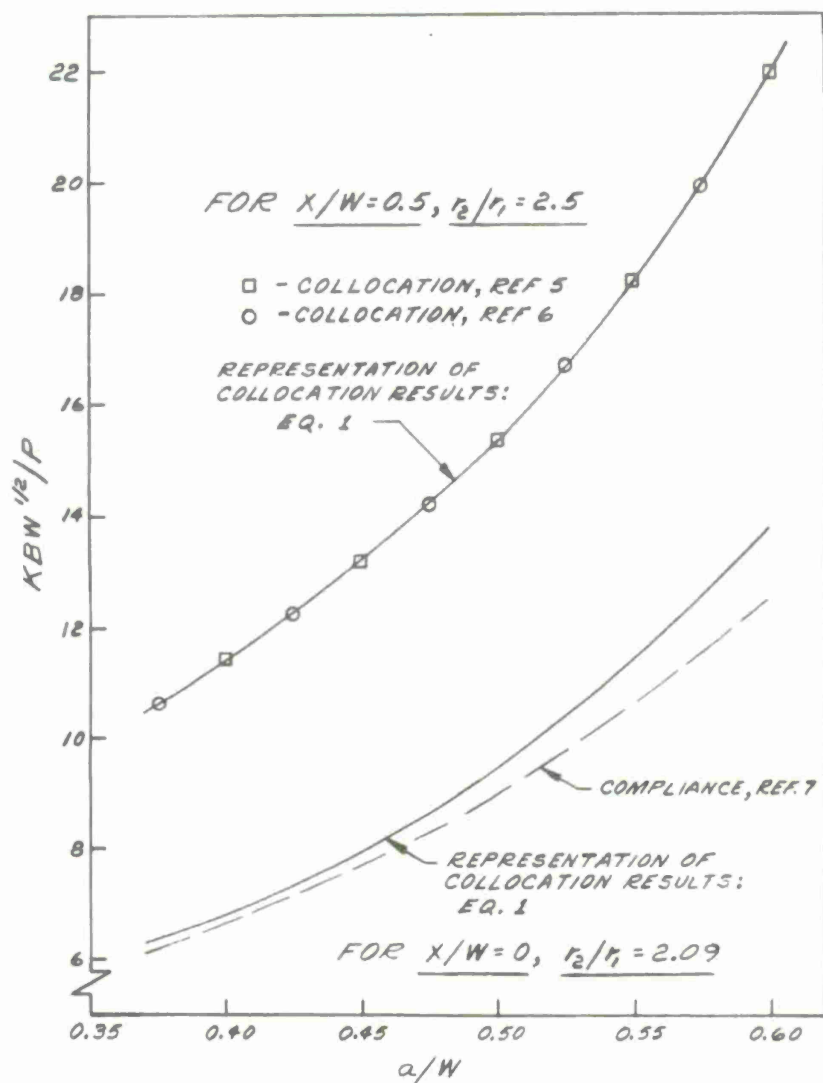
Figure 2.  Collocation and compliance K results for two
C-shaped geometries.

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and the results agree well with the more certain collocation results now available. Recently Mukherjee[7] has obtained compliance measurements and calculated K calibrations for C-shaped specimens of the same geometries which are under consideration as standard geometries for $K_{Ic}$ testing. So these results are of particular interest. The compliance K calibration for an X/W = 0 geometry is shown in Fig 2 and compared with the values from Eq 1 for the same geometry. The differences between the compliance data and the collocation results are attributed to inaccuracies in the compliance K calibration method. Particularly at the end points of the compliance data inaccuracies are unavoidable, but the generally good agreement is reassuring, and the compliance data is also useful for another purpose. This will be discussed in a later section.

COMPARISON OF C-SHAPED K CALIBRATION WITH OTHER GEOMETRIES

When outline sketches of C-shaped specimens are compared with straight bar and compact specimens, two geometries frequently used in fracture mechanics testing, some similarities are apparent. Figure 3 shows sketches of C-shaped specimens compared with the compact specimen and with the single-edge-notch bar specimen (usually abbreviated, the SEN specimen). In addition, the K calibrations for these geometries are shown. The K results for the C-shaped specimens are from Eq 1, and the K results for the compact and SEN specimens are from ref 8 and from ref 9 and 10 respectively.

[7]Mukherjee, B., "Stress-Intensity Calibration of C-Shaped Specimens by Compliance Method," Ontario Hydro Research Report, Toronto, Canada, to be published.

[8]Srawley, J. E., "Wide Range Stress Intensity Factor Expressions for ASTM E-399 Standard Fracture Toughness Specimens," NASA Tech Memo NASA TM X-71881, Lewis Research Center, Cleveland, Ohio, 1976.

[9]Brown, W. F., Jr. and Srawley, J. E., Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410, American Society for Testing and Materials, 1966.

[10]Srawley, J. E., and Gross, B., Engineering Fracture Mechanics, Vol 4, 1972, pp. 587-589.

## Compact Specimen

Considering first the comparison of the C-shaped and compact specimens, sketches 1, 2 and 3 in Fig 3 show the comparison which is made. The sketches indicate that C-shaped specimens with X/W = O are not much
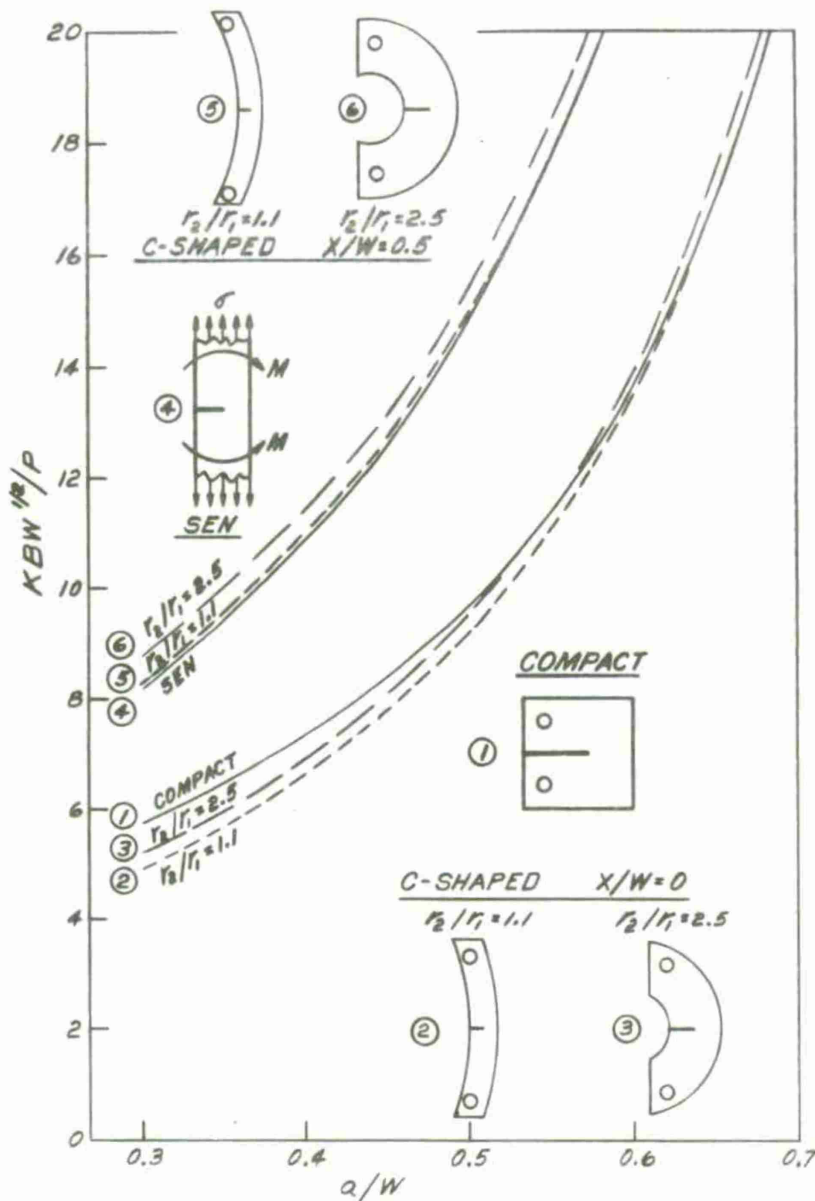


Figure 3. Comparison of K results for C-shaped and other specimens.

different from compact specimens with the same width and thickness dimensions,.
W and B. Both specimen types involve essentially the loading of a specimen
of width W with the loading in line with the notched edge of the specimen.
It is interesting to note that the curved boundaries of the C-shaped
specimens have only a small affect on K. This is indicated by the fact
that there is little difference between the K calibration for cases 2 and
3, whereas there is a large difference in radius ratio and thus in curvature
between cases 2 and 3. The most significant difference in K for compact
and C-shaped specimens is that K for the compact specimen is 10-20% higher
for shallow cracks, that is, for small values of a/W. This is due to the
smaller dimension of the compact specimen in the direction normal to the
crack plane, that is in the vertical direction as shown in the sketch.
For large values of a/W the remaining uncracked ligament dimension, which
is equivalent for both specimen types, becomes the controlling factor.
And the smaller vertical dimension of the compact specimen is no longer
very significant. The result for large a/W is that the K calibrations
for compact and C-shaped specimens become nearly equal.

### Straight Single-Edge-Notch Specimen

Sketches 4, 5 and 6 show the C-shaped specimens and the SEN specimen
which are compared. For C-shaped specimens with X/W = 0.5, some small
differences are observed in the K calibrations due to the effect of radius
ratio. But perhaps most interesting are the nearly identical results
(within 1%) from C-shaped specimens with a radius ratio of 1.1 and the SEN
specimen loaded by combined tensile stress and bending moment. This SEN
K calibration is obtained by adding the K for a notched bar under a remote
tension stress of P/BW to the K for a notched bar under a pure bending

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moment of P $(X+W/2) = PW$. The sum of these two known K calibrations[9][10] is shown as curve 4. This same curve, within a fraction of 1% can also be obtained from Gross and Srawley's recent work on C-shaped specimens.[6] Since the K of the C-shaped specimens is closely approximated by the K of a straight bar under equivalent tension and bending loads, it is clear that the curvature of C-shaped specimens with $X/W = 0.5$ has little effect on K. And the curvature effect becomes even less significant the deeper the crack.

SUGGESTED STANDARD $K_{Ic}$ TESTS WITH THE C-SHAPED SPECIMEN

Two important requirements for a standard $K_{Ic}$ test are a standard specimen geometry and a K calibration of known high accuracy. There are other important requirements but they will not be discussed at length here, because the C-shaped specimen is similar enough to the compact specimen that the $K_{Ic}$ test requirements already standardized for the compact specimen in ASTM E-399 apply directly or apply with minor modifications.

### Specimen Geometry

The standard specimen geometry which will meet the needs of most users is in fact two C-shaped geometries. They are shown in Fig 4. As discussed in the introduction of this report, the two geometries differ in the location of the loading holes. The specimen with $X/W = 0.5$ has the advantage of higher load efficiency, that is, for a given applied load the resulting K value is higher by about 60%. For combinations of large

6Gross, B., and Srawley, J. E., "Analysis of Radially Cracked Ring Segments Subject to Forces and Couples", NASA Tech Memo NASA TM X-71842, Lewis Research Center, Cleveland, Ohio, 1976.

9Brown, W. F., Jr. and Srawley, J. E.,"Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410, American Society for Testing and Materials, 1966.

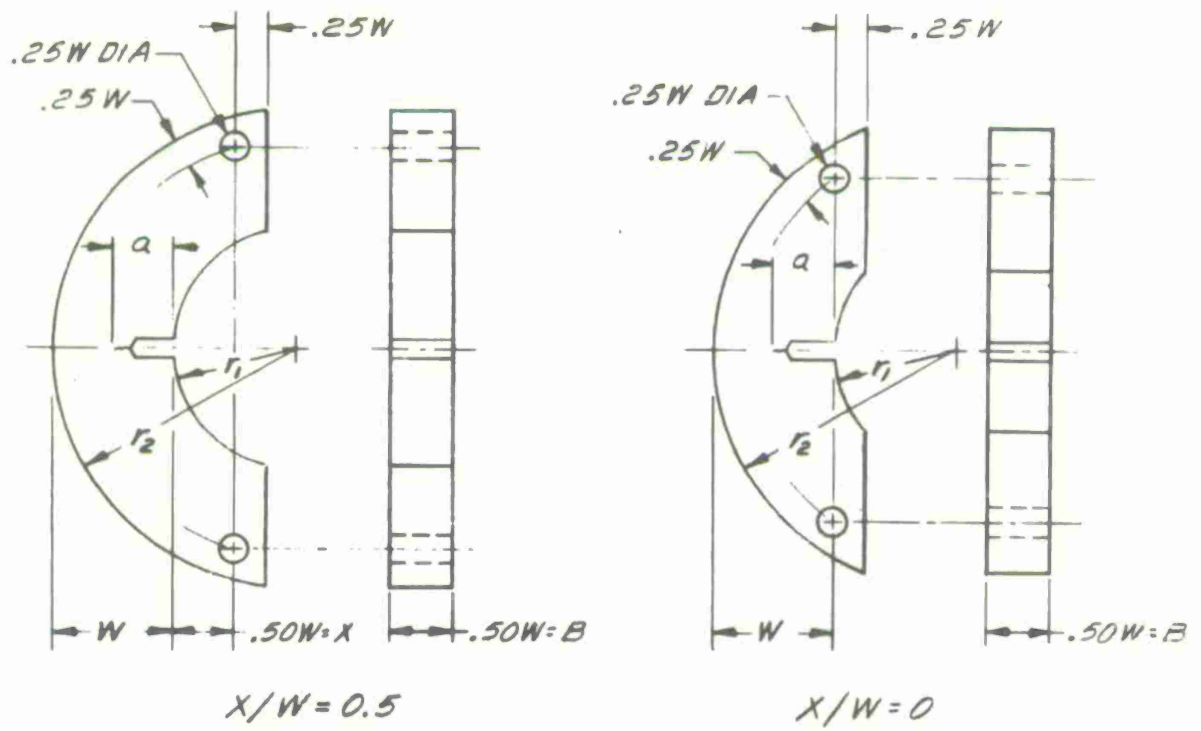10Srawley, J. E., and Gross, B., Engineering Fracture Mechanics, Vol 4, 1972, pp. 587-589.

Figure 4. Recommended standard C-shaped specimen geometry for $K_{Ic}$ tests.

specimens (large W) and materials with high $K_{Ic}$ the X/W = 0.5 specimen

may be the only choice for some users due to the load capacity of

available testing machines. The specimen with X/W = 0 has the advantage of

requiring a smaller portion of the disk from a given cylinder and has

a slight advantage in ease of machining in that the notch is easier to

produce. The notch is the same depth in both specimens from a given

cylinder, but the smaller total width dimension of the X/W = 0 specimen

will allow the use of a smaller milling cutter. In general, both specimen

geometries are patterned after the compact specimen, including such

dimensions as the loading hole diameter, h, and the specimen thickness, B.

## K Calibration for $K_{Ic}$ Tests

Equation 1 was selected as a good representation of the collocation

results over the relatively wide range of geometries indicated with the

equation. When that range is narrowed to the geometries of interest in

standard $K_{Ic}$ tests, the fit of Eq 1 to the collocation results is

significantly better. Equation 1 is repeated below with the narrow range

of variables applicable to $K_{Ic}$ tests.

$$KBW^{1/2}/P = f(a/W)[1+1.54 \ X/W + 0.50 \ a/W][1+0.22(1-a/W^{1/2})(1-r_1/r_2)]$$

$$f(a/W)=18.23 \ a/W^{1/2}-106.2 \ a/W^{3/2}+379.7 \ a/W^{5/2}-582.0 \ a/W^{7/2}+369.1 \ a/W^{9/2}$$

$$0.45 \leq a/W \leq 0.55 \qquad X/W = 0.0 \text{ and } 1.0 < r_2/r_1 \leq 10.0 \qquad \qquad Eq \quad 2$$
$$X/W = 0.5 \text{ and } 1.0 < r_2/r_1 \leq 3.0$$

For the narrow range of variables, we believe Eq 2 represents the true K

calibration for C-shaped specimens within 1%. This is based primarily on

the fact that Eq 2 fits both of the two independent sets of collocation

results[5][6] within 0.4% for the geometries indicated.

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[5]Underwood, J. H. and Kendall, D. P., "K Results and Comparisons for a
Proposed Standard C-Specimen", Benet Weapons Laboratory Technical Report
WVT-TR-74041, Watervliet, NY, Sep 1974.
[6]Gross, B. and Srawley, J. E., "Analysis of Radially Cracked Ring Segments
Subject to Forces and Couples", NASA Tech Memo NASA TM X-71842, Lewis
Research Center, Cleveland, Ohio, 1976.

For those who prefer a tabular form of the function, f(a/W), table below lists values of f(a/W) in the same form as in ASTM E-399.

Values of f(a/W) in Equation 2

| a/W | f(a/W) | a/W | f(a/W) |
|-----|--------|-----|--------|
| 0.450 | 6.32 | 0.505 | 7.45 |
| .455 | 6.42 | .510 | 7.57 |
| .460 | 6.51 | .515 | 7.69 |
| .465 | 6.60 | .520 | 7.81 |
| .470 | 6.70 | .525 | 7.94 |
| .475 | 6.80 | .530 | 8.07 |
| .480 | 6.90 | .535 | 8.20 |
| .485 | 7.01 | .540 | 8.34 |
| .490 | 7.11 | .545 | 8.48 |
| .495 | 7.22 | .550 | 8.62 |
| .500 | 7.33 | | |

### Test Procedure

As stated previously, the $K_{Ic}$ test procedure for C-shaped specimens is quite similar to the established procedure for compact specimens. The loading grips used for compact specimens can be used in all cases. For some C-shaped specimens with $r_2/r_1$ ratios near 1.0, the extension of the specimen above the top and below the bottom loading hole (see Fig 4) will be greater than the 0.5 W dimension which can be accomodated with standard compact grips. Removal of the portion of the specimen which interferes with the grip will not affect the test.

One of the main concerns in any fracture toughness test is the selection of a "measurement point". This is the point during the test at which a certain critical amount of crack extension occurs. In standard ASTM E-399 tests the measurement point is taken as the point at which a 5 percent decrease in the slope of the load vs crack mouth displacement curve occurs, i.e. a 5 percent increase in compliance. This has been shown to represent approximately 2 percent crack extension in both the bend and compact specimen for a/W = 0.5.

For the C-shaped specimen, there have now been three independent verifications of the 5% increase in compliance criteria. Gross and Srawley's collocation results[6] included displacement measurements which verified the 5% criteria. A compliance analysis[11] based on the K calibration also indicates that the 5% criteria is correct. Finally, Mukherjee's compliance measurements[7] give a direct verification of the 5% increase in compliance criteria for C-shaped specimens. For both specimen types his compliance measurements showed an increase of 5% when a crack at $a/W = 0.5$ was extended 2%.

### ASTM Standard Method of Test for C-Shaped Specimens

The inclusion of the C-shaped specimen as a third standard specimen geometry in ASTM E-399 has been accepted in principle by Subcommittee E24.01 on Fracture Mechanics Test Methods. In the near future, Task Group E24.01.12 on C-Shaped $K_{Ic}$ Specimens will initiate a round robin test program with C-shaped specimens. Concurrently, the task group in cooperation with Task Group E24.01.01 on Plane Strain Fracture Toughness Testing will prepare a draft revision to E-399 to incorporate the C-shaped specimen.

### OTHER FRACTURE MECHANICS TESTS WITH C-SHAPED SPECIMENS

In addition to plane strain fracture toughness $K_{Ic}$ testing discussed up to this point, the C-shaped specimen is convenient to use for other fracture mechanics tests of material in cylindrical shape.

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[6]Gross, B., and Srawley, J. E., "Analysis of Radially Cracked Ring Segments Subject to Forces and Couples", NASA Tech Memo NASA TM X-71842, Lewis Research Center, Cleveland, Ohio, 1976.

[7]Mukherjee, B., "Stress-Intensity Calibration of C-Shaped Specimens by Compliance Method", Ontario Hydro Research Report, Toronto, Canada, to be published.

[11]Kendall, D. P., Underwood, J. H., Winters, D. C., "Fracture Toughness Measurement and Ultrasonic Crack Measurement in Thick-Wall Cylinder Geometries", proceedings of Second Intern'l Conference on High Pressure Engineering, Brighton, England, July 1975, to be published.

## $J_{Ic}$ Tests

Measurement of fracture toughness of relatively tough materials using
small specimens is a common concern, and the J-integral approach to
fracture toughness measurements of this type is the most used. There is
an ASTM Task Group of Committee E-24 which is currently developing a $J_{Ic}$
fracture toughness test procedure. The C-shaped specimen is convenient
for measuring $J_{Ic}$ from cylindrical geometries for the same reasons already
discussed in relation to $K_{Ic}$ testing. The X/W = 0 specimen has the
further advantage in $J_{Ic}$ testing that the standard clip gage measurement
of crack-mouth displacement[1] can be used, since it is also the load-
line displacement for this specimen, see again Fig 4, and is effectively
equal to the load-point displacement which is required for a $J_{Ic}$ test.

The X/W = 0.5 specimen has the advantage of allowing a particularly
simple measurement of load-point displacement. As shown in Fig 5, if
center punch type indentations are made on the inner radius of the
specimen in line with the loading holes, then a spring loaded displacement
gage can be used to measure load-point displacement, and this method
requires no machining of the specimen. This is the test method we have
used for several years for $K_{Ic}$ and $J_{Ic}$ tests with C-shaped specimens.
Figure 6 shows a typical load-displacement plot (from ref 11) obtained
using this method. It is in fact no different from any plot obtained in
a proper fracture toughness test. But since the displacement is a
load-point displacement, then the total strain energy input into the

[1]1975 Annual Book of ASTM Standards, Part 10, American Society for Testing
   and Materials, 1975, pp. 561-589.
[11]Kendall, D. P., Underwood, J. H., Winters, D. C., "Fracture Toughness
    Measurement and Ultrasonic Crack Measurement in Thick-Wall Cylinder
    Geometries," proceedings of Second Intern'l Conference on High Pressure
    Engineering, Brighton, England, July 1975, to be published.

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specimen is simply calculated by measuring the area under the curve; and the measured strain energy input leads directly to a J value. The critical J value, when significant crack growth occurs, is $J_{Ic}$.
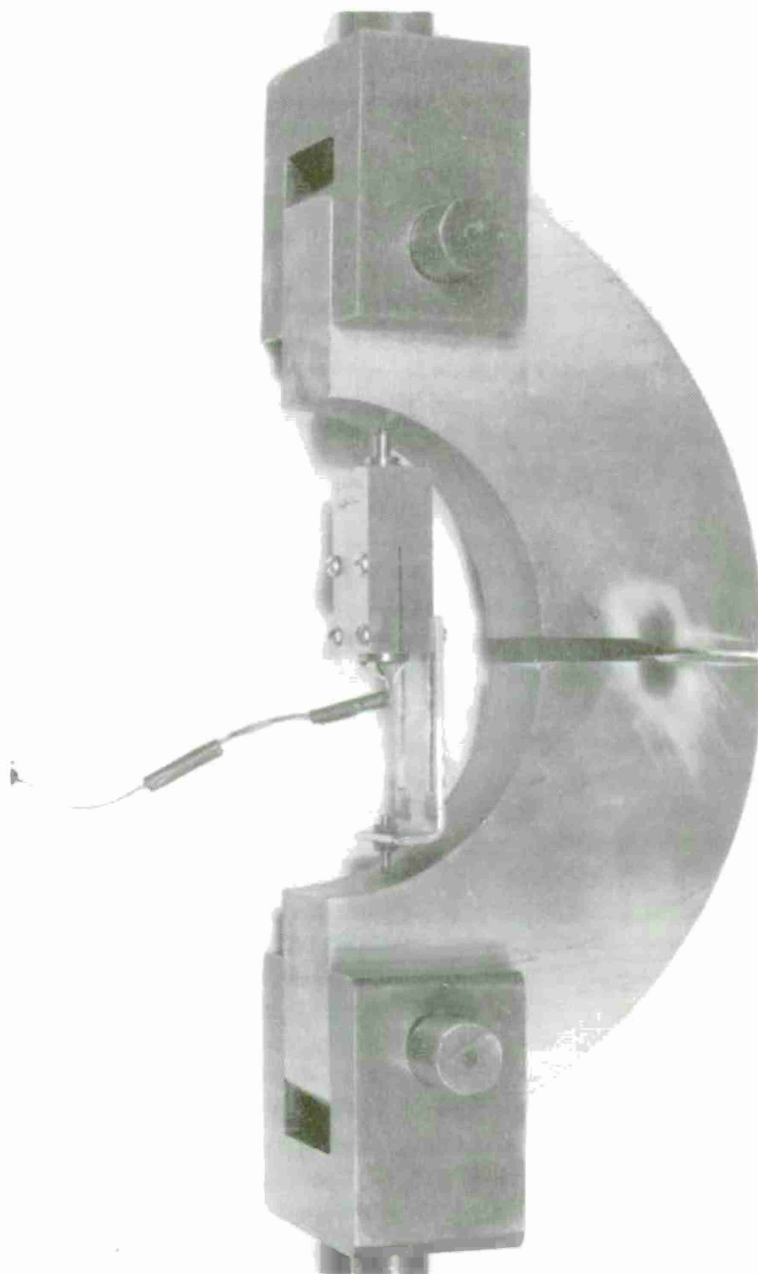


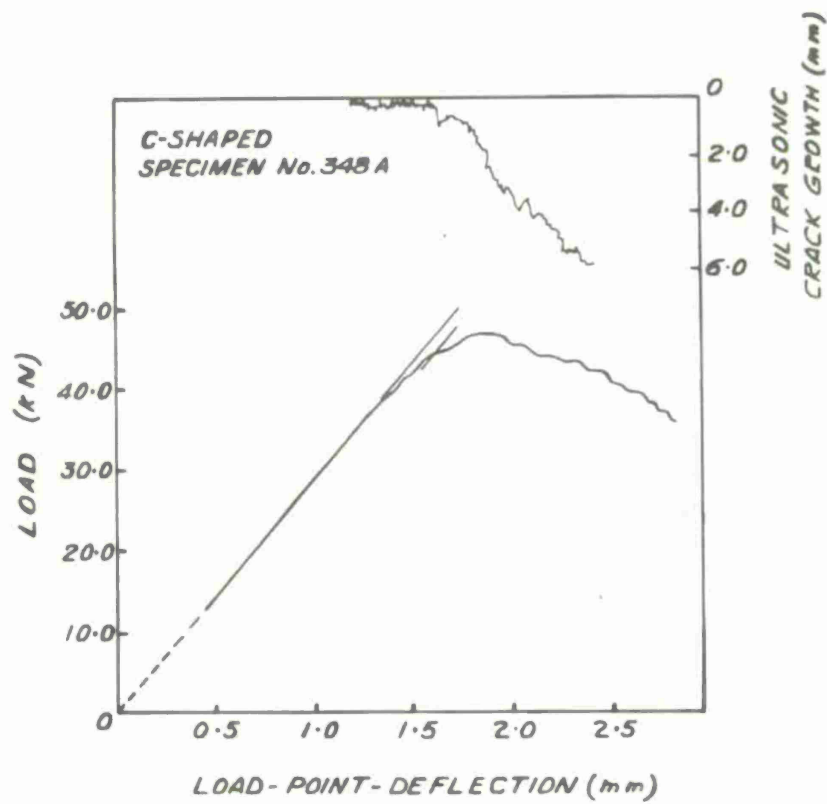Figure 5. Load-point-displacement test arrangement for X/W=0.5 specimen.

Figure 6. Load versus displacement and crack growth versus displacement for a C-shaped specimen.

## Crack Growth Measurements by Ultrasonics

The unique feature of the data in Fig 6 is that we obtain a continuous measurement of crack length and thus crack growth using ultrasonics. The ultrasonic method has been described in previous reports,[11][12][13] so it will not be discussed at length. In principle, it is as indicated in Fig 7 (applied to a compact specimen). For C-shaped specimens, as well as compact and bend specimens, we routinely obtain a continuous measure of crack growth by using a standard ultrasonic probe directed "end-on" at the crack tip. Two essential requirements are very high gain ultrasonic equipment and relatively clean, inclusion-free material. Using vacuum degassed Ni-Cr-Mo forged steel, we have no problems with the method.

The great advantage of the ultrasonic method is that with one specimen we can determine the point on the load-deflection curve at which a significant amount of crack growth has occurred, and this point corresponds to $J_{Ic}$. But it must be stated that the amount of crack growth which is "significant" for a $J_{Ic}$ determination is not yet established for any specimen. Only after further tests with various materials and conditions as part of ASTM Task Group E24.01.09 and by fracture mechanists in general will the criteria for $J_{Ic}$ determination become standardized.

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[11]Kendall, D. P., Underwood, J. H., Winters, D. C., "Fracture Toughness Measurement and Ultrasonic Crack Measurement in Thick-Wall Cylinder Geometries", proceedings of Second Intern'l Conference on High Pressure Engineering, Brighton, England, July 1975, to be published.

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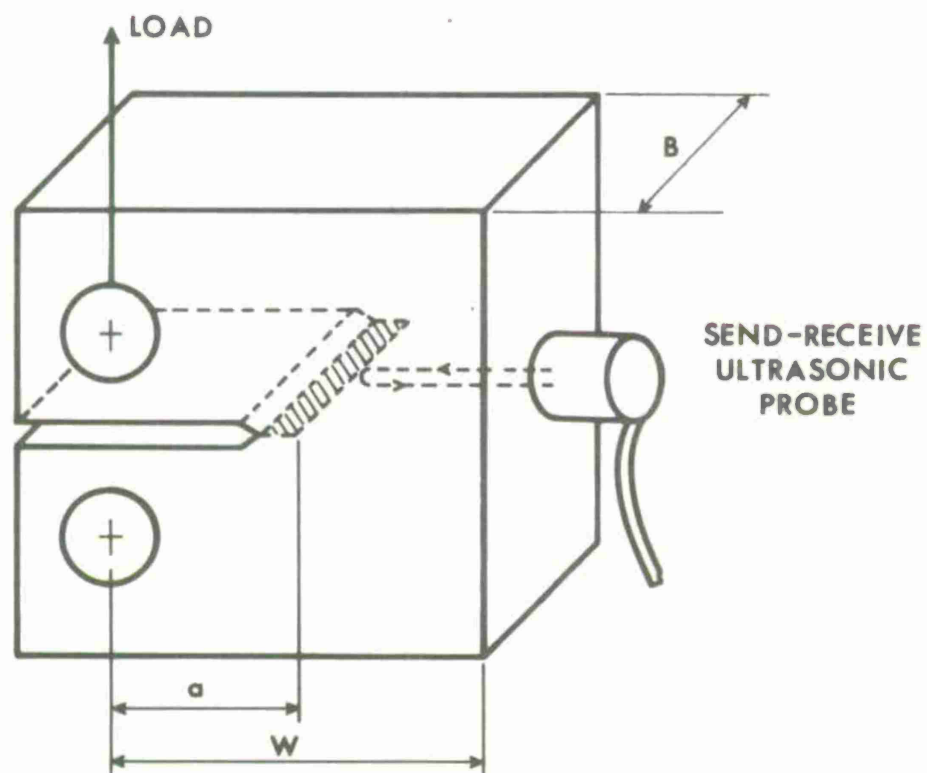
Figure 7.  Sketch of end-on ultrasonic crack growth measurement.

## Fatigue Crack Growth Tests

Finally, a few comments regarding fatigue crack growth tests with C-shaped specimens are offered. For cylindrical geometries, the C-shaped specimen can be used to advantage. By using the full wall thickness from a given cylinder, the total length of crack growth can be larger, and this leads to greater accuracy. The K calibration given by Eq 1 is believed to be sufficiently accurate to calculate the K values which are used to describe fatigue crack growth tests.

The choice of thickness for C-shaped fatigue crack growth specimens does present a problem. Most applications involving fatigue crack growth in cylinders are in pressure vessels which are long in the axial direction which corresponds to the thickness direction of the C-shaped specimen. This thickness should not be so large that the variation in crack depth between the specimen surface (where measurements are usually taken) and the specimen mid-thickness becomes significant. The common situation of a further advanced fatigue crack at mid-thickness is minimized by using specimens with small thickness-to-depth ratios. In general, the specimen thickness (B) should not exceed 0.25 W. Conversely, the specimen thickness should be large enough to assure plane strain conditions at the crack tip. The fact that the full cylinder wall thickness can be used for "W" in the C-shaped specimen helps in meeting the above requirements.

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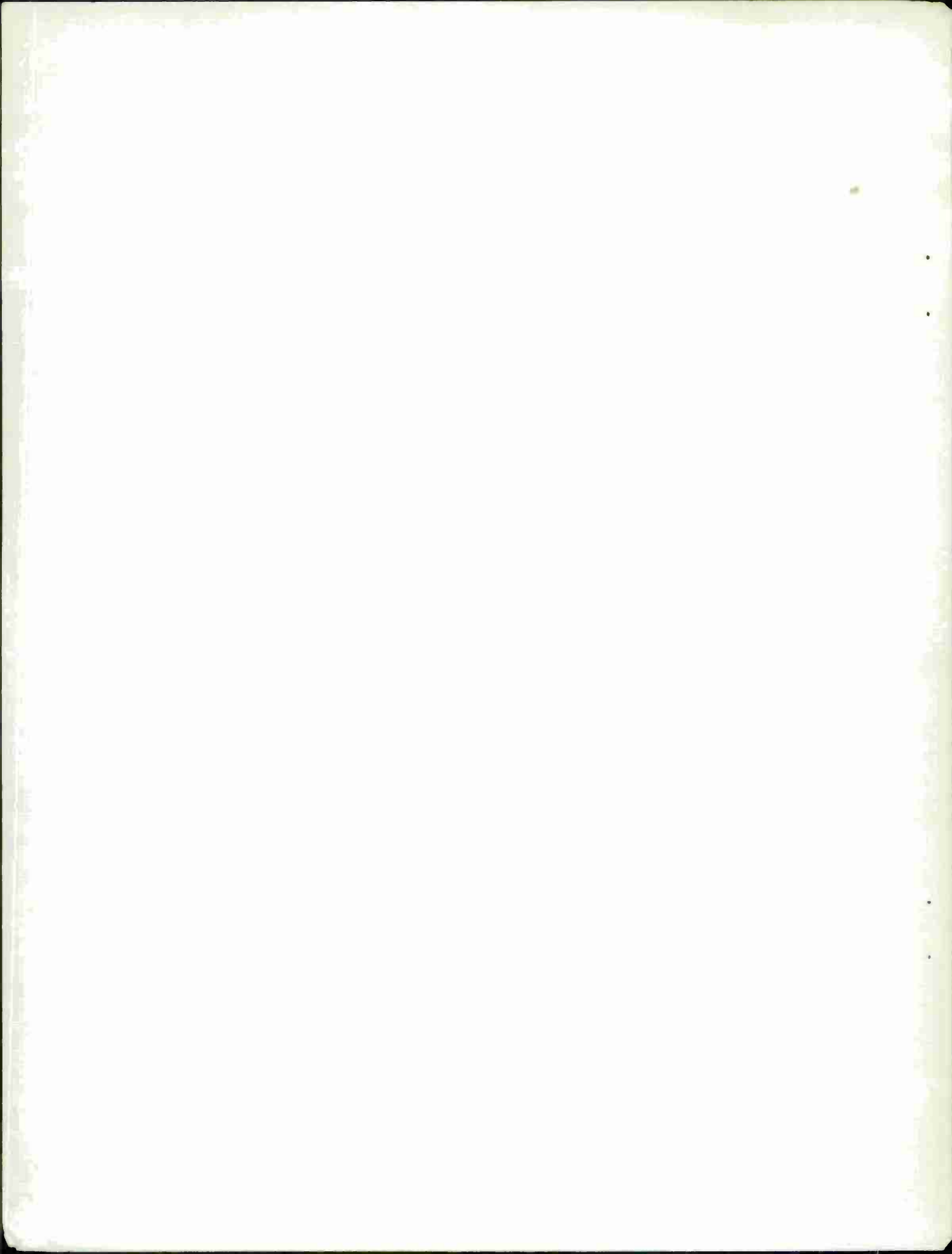1. *1975 Annual Book of ASTM Standards*, *Part 10*, American Society for Testing and Materials, 1975, pp. 561-580.

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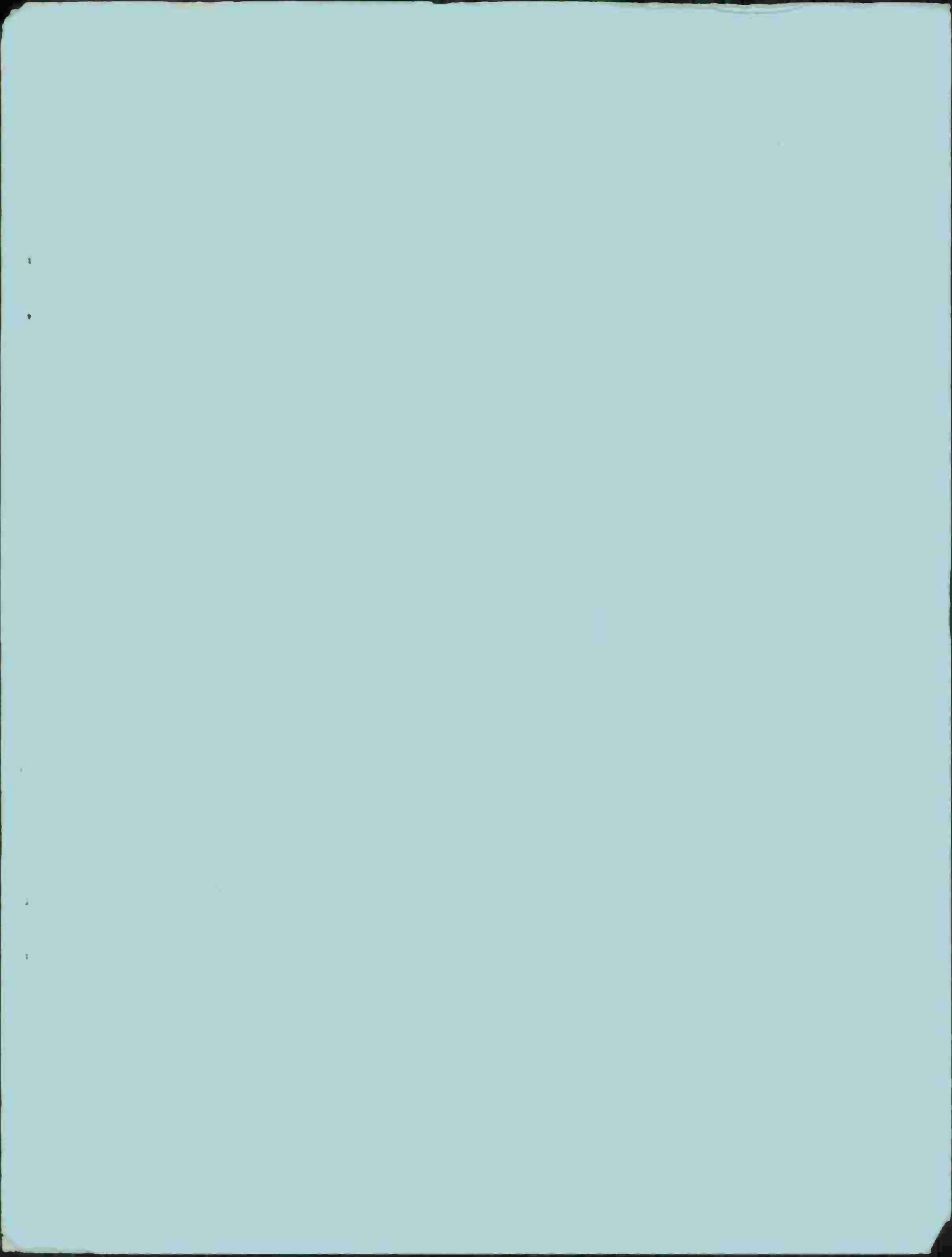WATERTOWN, MASS 02172

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